Performance of Road Embankment on Cement Stabilized Soft Clay

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ABSTRACT

Cement stabilization of soft clay has been growingly used as a ground improvement method. This paper evaluates the performance of a road embankment constructed on cement-stabilized soft clay (CSC). The undrained shear strength of the soft clay was experimentally determined before and after stabilization with cement. The results of the experimental work were used to simulate the behavior of the foundation soil under the road embankment using a 2-D finite element model. The foundation soil consisted of two layers: CSC having a variable thickness ranging from 1 to 5m, followed by soft clay layer extending to 15m below ground surface. The performance of the embankment founded on CSC was compared to that obtained if the CSC was replaced with compacted sand fill. Cement stabilization enhanced the performance of the embankment with respect to safety against shear failure more than sand soil replacement.

RÉSUMÉ

La stabilisation du ciment de l'argile molle a été utilisée d'une façon croissante comme une méthode d'amélioration des sols. Cet article évalue la performance d'un remblai de la route construit sur le ciment stabilisé de l'argile molle (CSC). La résistance au cisaillement de l'argile molle a été déterminée expérimentalement, avant et après la stabilisation avec le ciment. Les résultats des travaux expérimentaux ont été utilisés pour simuler le comportement du sol de fondation sous le remblai de la route en utilisant un modèle à éléments finis 2-D. Le sol de fondation composé de deux couches: CSC ayant une épaisseur variable allant de 1 à 5 m, suivie par la couche d'argile molle s'étendant jusqu'à 15 m sous la surface du sol. La performance de la digue fondée sur le CSC a été comparée à celle obtenue si le CSC a été remplacé par un remblai de sable compacté. La stabilisation au ciment a amélioré la performance de la digue en matière de sécurité contre la rupture par cisaillement plus que le remplacement du sol de sable.

1 INTRODUCTION

Construction on soft clay is challenging due to its low strength and high compressibility. Chemical stabilization of soft soils has been extensively used in both shallow and deep applications to improve inherent soil properties, such as strength and deformation behavior (Bergado et al, 1996; and Chen and Wang, 2006). As proposed by the AASHTO and FHWA (2002), stabilization of the upper 3 to 5m of soil materials either by mixing the soil with stabilizing agent (mass mixing) or by impact compaction is an optimum foundation improvement technique. Mass stabilization has proven to be an excellent ground improvement technique for soft soils as it saves time compared to other ground improvement techniques such as preloading (AASHTO and FHWA, 2002). The increased bearing capacity of chemically stabilized subgrade results in a reduction in the required thickness of the base course layer required to ensure prolonged serviceability of highways (Austroads, 1998). Mass stabilization of soft soils has recently become more feasible due to the development of commercial stabilization systems that can stabilize soft soils up to a depth of about 5m.

2 CEMENT STABILIZATION OF SOILS

Cement is used to bind soil particles to increase soft soil's strength and stiffness. Stabilization is done by mixing an appropriate amount of dry or wet cement throughout a volume of the soft soil. The increase of strength of cement-stabilized soils comes from the physico-chemical reactions between the soil and cement, such as the hydration of cement and the interaction between the substances in the soil and the products of the hydration of cement (Chen and Wang, 2006). Rodriguez et al. (1988) evaluated experimentally ranges of percentages of cement by weight to be tested initially for different soil types (Table 1).

Table 1. Percentages of cement to be tested initially for different types of soils (Rodriguez et al, 1988)

Type of soil	Percentage of cement by weight
GW, GP, GM, SW	3 – 8
SC, GC	5 – 9

SP, SM	7 – 11
ML	7 – 12
CL, OL, MH	8 – 13
CH	9 – 15
OH	10 – 16

The hardening process of cement stabilized soils happens immediately upon mixing soil with cement slurry. The hardening agent produces the hydrated calcium silicates, hydrated calcium aluminates, and calcium hydroxide and forms hardened cement bodies (Saitoh et al., 1985). The strength of the treated clay depends on the type of hardening agent (Porbaha et al., 2000). Kawasaki et al. (1981) used two types of cement, namely slag cement and ordinary Portland cement, to stabilize two different soils. They found that the improvement of soil characteristics depended on the chemical components of cementing agent and the properties of the soil.

The compressive strength of cement treated clay increased with the increase of curing time (Kawasaki et al., 1981; and Uddin, et al., 1997). Porbaha et al. (2000) observed that the compressive strength increased with rapid rate in the early curing periods and then it continued increasing with time but at a decreasing rate. Saitoh et al. (1996) reported that the compressive strength ratio at 28 days to 7 days ranged from 1.2 to 2.1.

Uddin et al. (1997) found that the final compressive strength of the stabilized clay increased with the increase of cement content. Taki and Yang (1991) measured the unconfined compressive strength of different soil types treated with cement. Coarse grained soil exhibited more increase in unconfined compressive strength compared to that obtained for fine grained soil mixed at the same cement content.

Typical undrained shear strength (c_u) of soil-cement mixtures were reported in the Federal Highway Administration Report No. FHWA-SA-98-086 (FHWA, 1998). The strength properties were obtained by performing unconfined compression tests on samples where the weight of dry cement to soil volume ranged typically from, 200 to 450kg/m^3. The undrained shear strength of the soil-cement mixtures depended on the undrained shear strength of the natural soil as shown in Equation 1. The upper limit of shear strength was usually obtained for higher cement content and/or cohesionless soils and the lower limit was usually obtained for lower cement content and/or cohesive soils.

$$c_{u(soil\text{-}cement)} = 10 \text{ to } 50\ c_{u(soil)} \qquad [1]$$

3 EXPERIMENTAL WORK

3.1 Characterization of Tested Soil

Tests were conducted on saturated soft clay obtained from the Delta region of Egypt to determine its physical and mechanical properties before and after mixing with cement (Saadeldin, 2009). The grain size distribution of the natural soft clay composes of 4.9% sand, 16.1% silt, and 79.0% clay. The natural soft clay has a liquid limit of 80%, plastic limit of 30%, and field water content of 69%. According to the Unified Soil Classification System (USCS), the soil is classified as high plasticity clay (CH). The above and other physical properties of the soft clay are summarized in Table 2.

Table 2. Geotechnical index properties of tested soft clay.

Characteristics	Value
Natural Water Content (%)	69
Bulk/Saturated Unit Weight (kN/m^3)	15.8
Void Ratio	1.81
Specific Gravity	2.62
Liquid Limit (%)	80
Plastic Limit (%)	30
Sand (%)	4.9
Silt (%)	16.1
Clay (%)	79

Unconfined compression tests (ASTM D2166) were conducted on the soft clay, which had an unconfined compressive strength of about 24kPa. One-dimensional consolidation test (ASTM D2435) was conducted on the soft clay, and the e-log σ_v' curve is shown in Figure 1, where σ_v' is the effective vertical stress. The clay was normally consolidated with compression index of 0.82 and preconsolidation pressure of 60kPa.

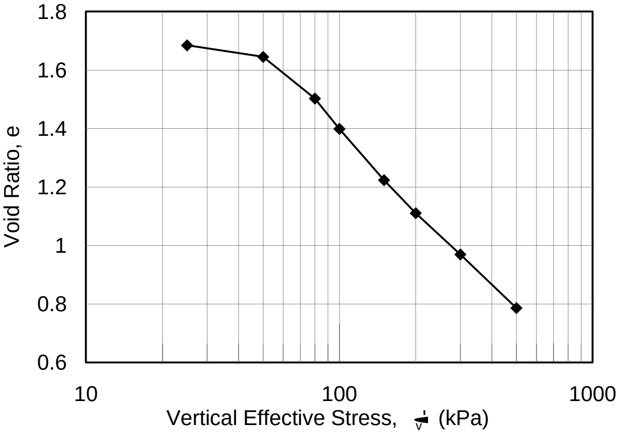

Figure 1. e-log σ_v' curve of tested soft clay

3.2 Cemented Soft Clay Preparation

Soft clay specimens were extracted from the Shelby tubes, and placed in a standard laboratory mixer to remold the soft clay for about five minutes at its natural water content. Ordinary Portland cement was used for chemical stabilization. Target amount of cement was carefully weighed, and then mixed with water to form slurry using water/cement ratio of 0.25 (Oh, 2007). The cement slurry was then slowly added to the remolded clay, and then further mixed for a period of five minutes until the mix was visually homogenous. Cement stabilization was investigated for cement contents (A_w) of 5%, 10%, and 15%.

The soil was statically compacted using a hydraulic jack in a brass mold 50mm in diameter and 150mm tall. The compaction mold was then placed in a specially fabricated extrusion apparatus, where the hydraulic jack was used to vertically push the compacted samples out of the mold. Each sample was sealed and stored in a humidifying chamber for curing times of 3, 7, 28, and 56 days. Unconfined compression tests (ASTM D2166) were then conducted on cured cement-stabilized samples.

3.3 Effect of Curing time on Unconfined Compressive Strength of Cement-Stabilized Soft Clay

The effect of curing time on unconfined compressive strength of cement-stabilized soft clay (CSC) is shown in Figure 2. For tested cement contents, the unconfined compressive strength increased as the curing time increased up to about 28 days, after which compressive strength practically stabilized. Therefore, the undrained shear strength of CSC was assumed to correspond to curing time of 28 days. For tested cement contents, the unconfined compressive strength (q_u) ratio at 28 days to 7 days ranged from 1.8 to 2.1, which is in agreement with the range reported by Saitoh et al. (1996).

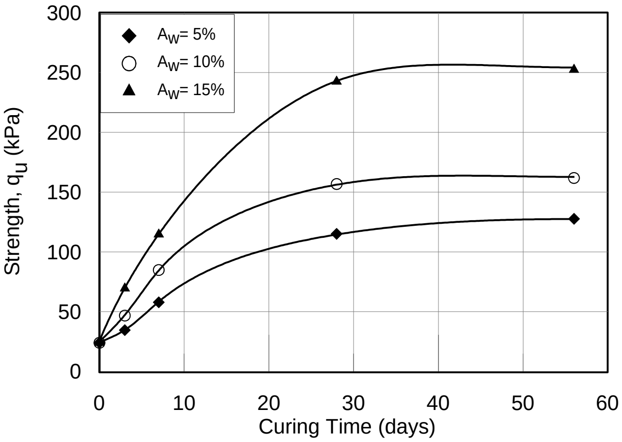

Figure 2. Effect of curing time on unconfined compressive strength of cement-stabilized soft clay soil for different cement contents

3.4 Effect of Cement Content on Unconfined Compressive Strength of Cement-Stabilized Soft Clay

Stress-strain curves of cement-stabilized soft clay tested at curing time of 28 days for different cement contents are shown in Figure 3. As the cement content increased, the unconfined compressive strength increased and the stress-strain curves exhibited more pronounced peaks occurring at smaller strains. For cement content of 15% and curing time of 28 days, the unconfined compressive strength (q_u) increased to about 10 times, from 24kPa for natural soft clay to 242kPa for CSC, which is in agreement with the findings reported by FHWA (1998) and presented above in Equation 1.

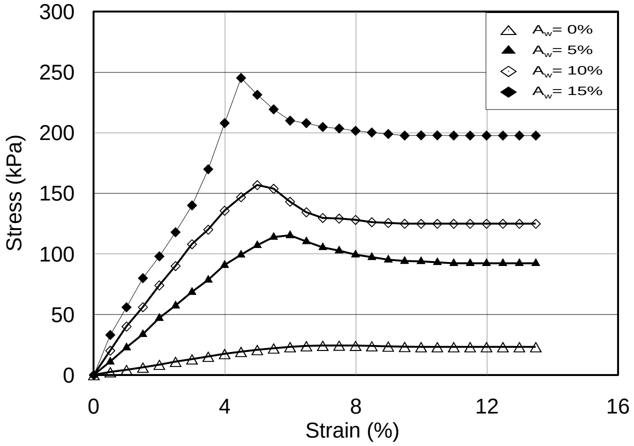

Figure 3. Stress-strain curves of cement-stabilized soft clay for different cement contents

4 FINITE ELEMENT ANALYSIS

4.1 Geometry

The performance of a typical road embankment (2m-high, 16m-wide) founded on soft clay was predicted using plain strain finite element program; PLAXIS-2D-V8. The soft clay deposit in the studied model extended to 15m below ground surface. The road embankment was expected to encounter stability and serviceability problems due to the softness of the foundation soil. Two alternatives were studied and compared to improve the performance of the embankment. The first alternative was to improve the soft clay by cement stabilization. The second alternative was to replace the upper portion of the soft clay with compacted sand fill. The road embankment dimensions and its properties were kept constant while the underneath soil profile was changed throughout all analyzed cases. The underneath soil profile consisted of two layers: the first layer was either CSC or compacted sand fill, while the second layer was soft clay (Figure 4). Additional surcharge load (q) ranging from 10 to 50kPa was added on top of the embankment to simulate different levels of loading on the road embankment.

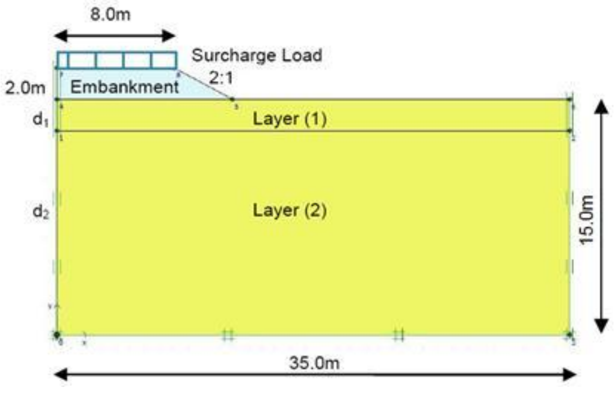

Figure 4. Ground profile and road embankment dimensions used in finite element analyses

4.2 Soil Modelling

Hardening Soil (HS) model was selected to simulate the behavior of the soft clay layer. This model is capable of simulating the behavior of soft soils and it accounts for the increase of stiffness with pressure, which was considered essential for modeling the foundation soil extending to relatively large depths underneath the embankment (15m). Mohr-Coulomb (MC) model was selected to simulate the behavior of CSC and compacted sand extending to relatively shallow depths ranging from 1 to 5m under the embankment. MC model doesn’t account for increase of stiffness with pressure, which was considered acceptable for the range of depths studied herein. Three phases were used to model the embankment:

- Generation of initial stresses.
- Modeling the construction of embankment and surcharge load.
- Computing the factor of safety against shear failure, which was critical for undrained conditions, and computing the deformations of the embankment, which were maximum for drained conditions.

Modeling of soft clay was done for drained and undrained conditions. Effective (drained) strength parameters were used for drained conditions, and total (undrained) strength parameters were used for undrained conditions.

The CSC was assumed to experience minimal volume changes upon loading for both drained and undrained conditions, which may be neglected. Accordingly, the CSC was modeled using total (undrained) strength parameters evaluated from unconfined compressive strength conducted on cement-stabilized samples. The compacted sand was modeled using effective (drained) strength parameters.

4.3 Soil Data Set Parameters

The input parameters used in modeling the soft clay layer are presented in Table 3, and the input parameters for the CSC and compacted sand are presented in Table 4. The characteristics of the soft clay and CSC were mostly evaluated experimentally. The characteristics of the compacted sand were taken equivalent to that of dense Hostun sand evaluated by Amat (2007).

4.4 Validation of HS model for Soft Clay Layer

The input parameters used in the HS model for soft clay layer were verified using an axisymmetric model, 1m in diameter and 5m deep, subject to vertical total stress of 500kPa as shown in Figure 5. First, the results of the 1-D consolidation test conducted on the soft clay sample were used to calculate the expected settlement of this model using Terzaghi’s 1-D theory of consolidation (Terzaghi, 1943). Second, displacements were evaluated using PLAXIS with the assumed HS input parameters. Finally, the calculated settlement using Terzaghi’s 1-D theory of consolidation was compared to that obtained using PLAXIS.

Table 3. Input parameters used in Hardening-Soil (HS) model for soft clay layer

Parameter	Undrained	Drained
Saturated unit weight (kN/m^3)	15.8	15.8
Cohesion (kPa)	12	1
Friction angle (Degree)	0	25.6
Dilatancy (Degree)	0	0
Stiffness (kPa)	430	430
Tangent stiffness (kPa)	500	500
Power (m)	1	1
Horizontal permeability (cm/sec)	1×10^{-6}	1×10^{-6}
Vertical permeability (cm/sec)	1×10^{-6}	1×10^{-6}
Initial void ratio	1.81	1.81
Unloading / reloading stiffness (kPa)	1300	1300
Poisson's ratio	0.45	0.2
Reference stress for stiffness’s (kPa)	62	62
Coefficient of lateral stress in normal consolidation	1	0.568
Failure ratio	0.9	0.9

Table 4. Input parameters used for CSC and compacted sand fill

Parameter	CSC	Compacted Sand Fill
Saturated unit weight (kN/m^3)	18.5	20
Cohesion (kPa)	121	1
Friction angle (Degree)	0	41
Dilatancy (Degree)	0	14
Stiffness (kPa)	5000	37000
Initial void ratio	0.9	1
Poisson's ratio	0.2	0.3

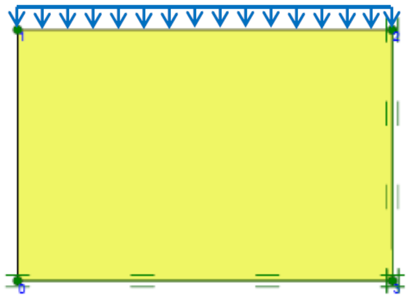

Figure 5. Axisymmetric soft clay soil validation model

The displacement evaluated using the finite element analysis with the HS input parameters presented in Table 3 was 7% higher than those calculated using Terzaghi's 1-D theory of consolidation. The 7% difference was considered acceptable.

5 RESULTS OF FINITE ELEMENT ANALYSES AND DISCUSSION

5.1 Factor of Safety against Shear Failure – Soft Clay

The short term factor of safety against shear failure was predicted for different surcharge loadings ranging from 10 to 50kPa using the strength reduction method. In case of founding the road embankment on natural soft clay, the factor of safety was 1.4 for surcharge load of 10kPa and decreased to about 0.8 for surcharge load of 50kPa as shown in Figure 6.

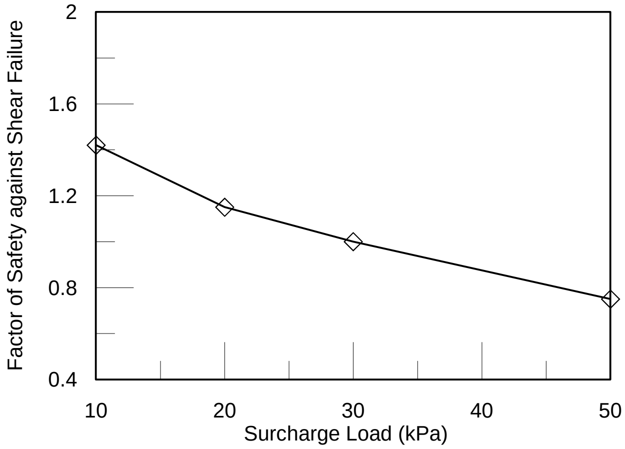

Figure 6. Variation of factor of safety against shear failure with load intensity for embankment on soft clay

5.2 Total Surface Settlement – Soft Clay

The long term total ground surface settlements were predicted for different surcharge loadings ranging from 10 to 50kPa. The variation of the predicted total surface settlement with load intensity for embankment founded on natural soft clay is shown in Figure 7. For a surcharge load of 10kPa, the maximum surface settlement was about 2.0m, and the surface settlement increased to about 3.5m in case of surcharge load of 50kPa.

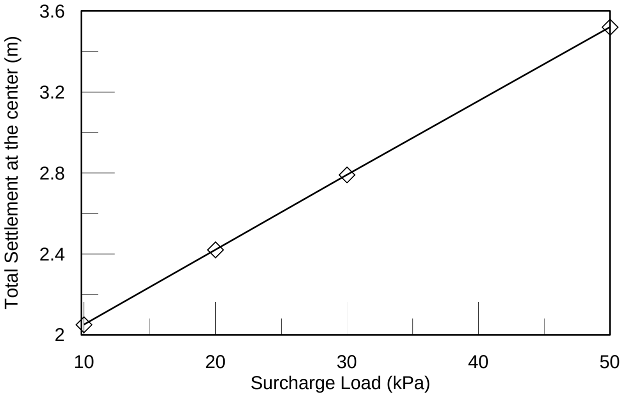

Figure 7. Variation of total settlement with load intensity for embankment on soft clay

5.3 Comparison between Cement Stabilization and Soil Replacement with respect to Factor of Safety against Shear Failure

Evaluated factors of safety in case of founding the road embankment on CSC or replacement soil are normalized to factors of safety obtained in case of founding the embankment on natural soft clay. The effects of cement stabilization and soil replacement depths on normalized factor of safety against shear failure are shown in Figure 8. Normalized factor of safety increased linearly with increase of stabilization depth by about 21% for each additional meter of cement stabilization depth, and by about 10% for each additional meter of replacement depth. Cement stabilization had a greater effect on increasing the factor of safety than soil replacement. For an average surcharge load of 30kPa and a target factor of safety of 1.5, the required cement stabilization depth was 2.4m versus 5m if soil replacement was applied (Saadeldin, 2009).

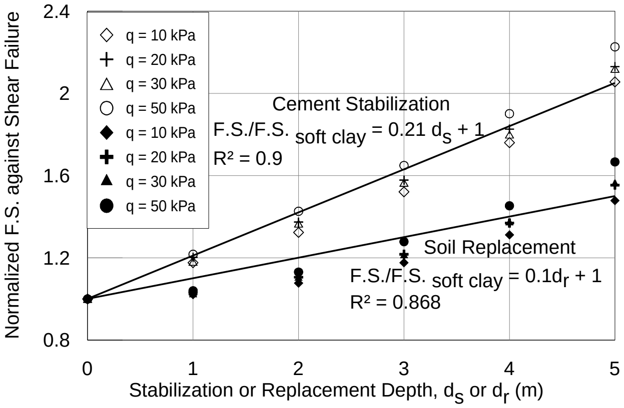

Figure 8. Effects of cement stabilization & soil replacement depths on factor of safety against shear failure

5.4 Comparison between Cement Stabilization and Soil Replacement with respect to Surface Settlement

Evaluated total ground surface settlements in case of founding the road embankment on CSC or replacement soil are normalized to settlements obtained in case of founding the embankment on natural soft clay. The effects of cement stabilization and soil replacement depths on the normalized ground surface settlement are shown in Figure 9. No significant difference was observed between the effect of cement stabilization and soil replacement on reducing ground surface settlement. The main component of predicted settlement is due to consolidation of the soft clay layer, which is the same for both improvement solutions. The minor predicted differences were due to the differences in the settlement of the compacted sand fill and the CSC.

For the range of stabilization depths considered, the relationship between stabilization depth and normalized surface settlement can be reasonably represented by a linear fit. Normalized surface settlement decreased by approximately 15% for each additional meter of cement stabilization depth and decreased by approximately 17% for each additional meter of replacement depth (Saadeldin, 2009).

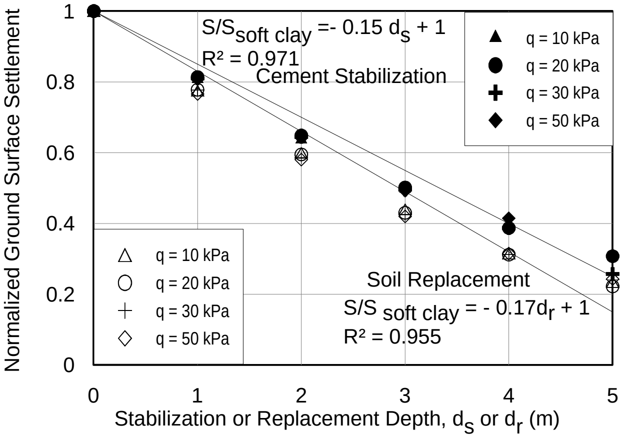

Figure 9. Effects of cement stabilization & soil replacement depths on normalized ground surface settlement

6 CONCLUSIONS

1. Cement is used as soil stabilizer to improve the mechanical properties of natural soft clay. The unconfined compressive strength of cement-stabilized soft clay increased as the cement content increased. The unconfined compressive strength increased as the curing time increased up to about 28 days, after which the compressive strength practically stabilized.

2. In case of using cement stabilization for ground improvement :

- Normalized factor of safety ($F.S./F.S._{soft\ clay}$) against shear strength failure increased linearly with the increase of stabilization depth by about 21% for each additional meter of stabilization depth.
- For the range of stabilization depths considered, the relationship between stabilization depth and normalized surface settlement can be reasonably represented by a linear fit. Normalized surface settlement decreased by approximately 15% for each additional meter of stabilization depth.

3. In case of using soil replacement (compacted sand) for ground improvement:

- Normalized factor of safety ($F.S./F.S._{soft\ clay}$) against shear strength failure increased approximately linearly with the increase of replacement depth by about 10% for each additional meter of replacement depth.
- For the range of replacement depths considered, the relationship between replacement depth and normalized surface settlement can be reasonably represented by a linear fit. Normalized surface settlement decreased by about 17% for each additional meter of replacement depth.

4. Cement stabilization enhanced the performance of the embankment with respect to safety against shear failure more than soil replacement. Both cement stabilization and soil replacement gave comparable results with respect to reducing total settlements.

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